Micromegas μTPC for direct Dark Matter search with MIMAC

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Abstract. The MIMAC project is a multi-chamber detector for Dark Matter search, aiming at measuring both track and ionization with a matrix of micromegas μTPC filled with ^{3}He and CF_4. Recent experimental results on the first measurements of the Helium quenching factor at low energy (1 keV recoil) are presented, together with the first simulation of the track reconstruction. Recontruction of track of α from Radon impurities is shown as a first proof of concept.

1. Introduction

Tremendous experimental efforts on a host of techniques have been made in the field of direct search of non-baryonic dark matter. However, going further required an unambigious positive signal in order to distinguish a geniune WIMP event from backgrounds (mainly neutrons and γ-rays). The most promising strategy is to search for a correlation of the signal with the motion of the detector with respect to the galactic Dark Matter halo. This can either be an annual modulation, due to the motion of the earth around the sun or a strong direction dependence of the incoming WIMP, toward the Cygnus constellation to which points the sun's velocity vector [1, 2]. Several projects aiming at directional detection of Dark Matter are being developed [3, 4, 5, 6].

Gaseous μTPC detectors present the privileged features of being able to reconstruct the track of the recoil following the interaction, thus allowing to access both the energy and the track properties (lenght and direction). A precise measurement of the energy of the recoil is the starting point of any background discrimination.

2. The MIMAC project

The MIMAC project is a multi-chamber detector for Dark Matter search. The idea is to measure both track and ionization with a matrix of micromegas μTPC filled with ^{3}He and CF_4. The use of these two gases is motivated by their privileged features for dark matter search. In particular, a detector made of such targets will be sensitive to the spin-dependent interaction, leading to a natural complementarity with existing detectors mainly sensitive to scalar interaction, in various SUSY models, e.g. non-universal SUSY [7, 8]. Moreover, as shown in [8], a 10 kg ^{3}He dark matter
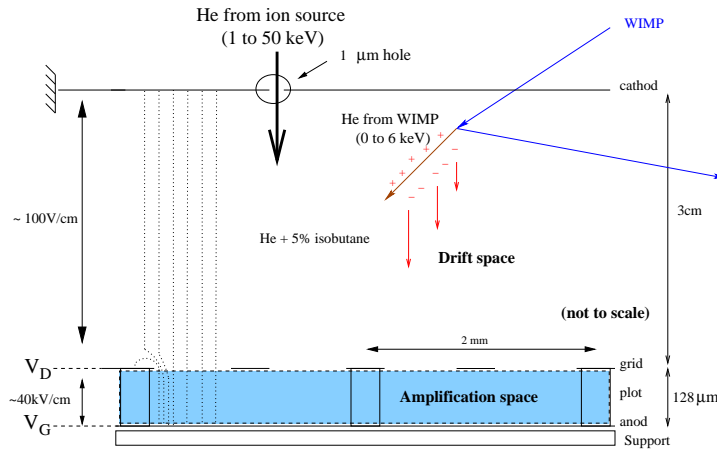
Figure 1. Sketch of the Micromegas μTPC used for the Quenching factor measurement (not to scale).

detector[1] with a 1 keV threshold (MIMAC) would present a sensitivity to SUSY models allowed by present cosmology and accelerator constraints. This study highlights the complementarity of this experiment with most of current spin-dependent experiments : proton based detectors as well as ν telescopes.

Using both ^{3}He and CF_4 in a patchy matrix of μTPC opens the possibility to compare rates for two atomic masses, and to study neutralino interaction separately with neutron and proton as the main contribution to the spin content of these nuclei. With low mass targets, the challenge is also to measure low energy recoils, below 6 keV for Helium, by means of ionization measurements. Low pressure operation of the MIMAC detector will open the possibility to discriminate neutralino signal and background on the basis of track features and directionality.

3. Ionization quenching factor measurement

The ionization quenching factor (IQF) is defined as the fraction of energy released through ionization by a recoil in a medium compared with its kinetic energy. Measuring IQF, especially at low energies, is a key point for Dark Matter detectors, since it is needed to evaluate the nucleus recoil energy and hence the WIMP kinematics.

The energy released by a particle in a medium produces in an interrelated way three different processes: i) ionization, producing a number of electron - ion pairs, ii) scintillation, producing a number of photons through de-excitation of quasi-molecular states and iii) heat produced essentially by the motion of nuclei and electrons. The fraction of energy given to electrons has been estimated theoretically [9] and parametrized by [10].

In the last decades an important effort has been made to measure the IQF in different materials : gases [11], solids [12, 13] and liquids [14], using different techniques. The use of a monoenergetic neutron beam has been explored in solids with success [15, 16]. However in the low energy range the measurements are rare or absent for many targets (e.g. Helium) due to ionization threshold of detectors and experimental constraints.

We have developed an experimental setup devoted to the measurement of low energy (a few keV) ionization quenching factor. The purpose is twofold : measuring for the first time the Helium quenching factor and performing very low energy measurements to test the prototype cell (resolution, threshold, ...) in the range of interest for Dark Matter.
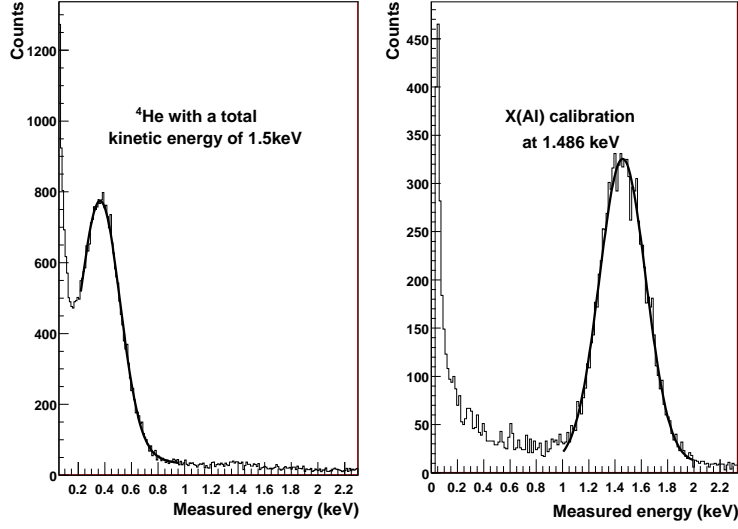
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[1] or the equivalent mass of CF_4

Figure 2. Spectra of 1.5 keV kinetic energy ^{4}He (left) and 1.486 keV X-ray of ^{27}Al (right) in ^{4}He +5% C_4H_{10} mixture at 700 mbar.

The experimental set-up is the following : an Electron Cyclotron Resonance Ion Source [17] with an extraction potential from a fraction of kV up to 50 kV, is coupled to Micromegas (micromesh gaseous) detector via a 1 μm hole with a differential pumping (fig. 1).
Ion energy values have been previously checked by a time-of-flight measurements through a 50 nm thick N_4Si_3 foil [18]. The ionization produced in the gas has then been measured with a Micromegas (micromesh gaseous) detector [19] adapted to a cathode integrated mechanically to the interface of the ion source. The μ-TPC is composed of a bulk type Micromegas [20], in which the grid and the anode are built and integrated with a fixed gap, 128 μm for measurements between 350 and 1300 mbar. The electric fields for the drift and the avalanche have been selected to optimize the transparence of the grid and the gain for each ion energy. Typical applied field were 100 V/cm for the drift and a voltage of 450 V for the avalanche. The drift distance between the cathode and the grid was 3 cm, large enough to include the tracks of ^{4}He nuclei of energies up to 50 keV. These tracks, of the order of 6 mm for 50 keV, are roughly of the same length than the electrons tracks produced by the X-rays emitted by th ^{55}Fe source used for calibration.

In order to measure the quenching factor of ^{4}He in a gas mixture of 95% of ^{4}He and 5% of isobutane (C_4H_{10}) we proceed as follows: i) the ionization given by the Micromegas was calibrated by the two X-rays (1.486 and 5.97 keV) at each working point of the Micromegas defined by the drift voltage (V_d), the gain voltage (V_g) and the pressure, ii) the number of ions per seconde sent was kept lower than 25, to prevent any problem of recombination in primary charge collection or space charge effect.

Two different calibration sources have been used : the 1.486 keV X-rays of ^{27}Al produced by alpha particles emitted by a source of ^{244}Cm under a thin foil of aluminium and a standard ^{55}Fe X-ray source giving the 5.9 keV K_α and the 6.4 keV K_β lines. These two lines, as they were not resolved by our detector, have been considered as a single one of 5.97 keV, taking into account their relative intensities. The IQF of a recoil is then the ratio between the ionization energy and the recoil kinetic energy. In such a way, the IQF compares the nuclei ionization efficiency with respect to the electrons. The ionization spectra of 1.5 keV ^{4}He nuclei and of electrons of
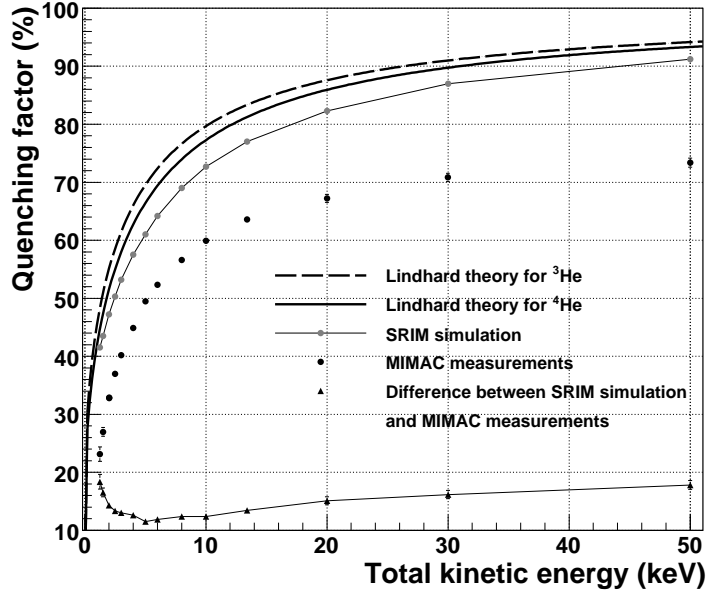
Figure 3. Helium ionization quenching factor as a function of ^{4}He kinetic energy (keV). Lindhard theory prediction (^{4}He in pure ^{4}He and ^{3}He in pure ^{3}He), parametrized as in [10], is presented and compared with SRIM simulation results (solid line and points) in the case of ^{4}He in ^{4}He +5% C_4H_{10} mixture. Measured quenching factor are presented at 700 mbar with error bars included mainly dominated by systematic errors. The differences between data and SRIM simulation are shown by triangles.

roughly the same energy (1.486 keV) are shown on Figure 3.

The measurement reported [21] have been focused on the low energy ^{4}He IQF. Figure 3 presents the results at 700 mbar compared with the Lindhard theory for ^{4}He ions in pure ^{4}He and with respect to the SRIM simulation [22] for ^{4}He in the same gas mixture used during the measurements. We observe a difference between the SRIM simulation and the experimental points of up to 20% of the kinetic energy of the nuclei, shown in fig. 3. This difference may be assigned to the scintillation produced by the ^{4}He nuclei in ^{4}He gas. This difference is reduced at lower pressures due to the fact that the amount of scintillation is reduced when the nuclei mean distance is increased giving a lower production probability of eximer states. More details may be found in [21].

As shown in [23] energy resolution of Micromegas μTPC has been measured down to 1 keV. Moreover, it does not depend on pressure and it does not affect the number of expected events for Dark Matter, even at low energy. Threshold as low as 300 eV (ionization) has been reached. As presented in [21], measurements have been done in various experimental conditions, showing a clear increase at lower gas pressure and also at lower isobutane percentage (the quencher). Hence, the ionization signal is expected to increase with Helium purity, which is needed for Dark Matter search, and also at the lowest pressures, which is compulsory for directional detection.

4. Track simulation and measurement

The second step of a dark matter project aiming at directional detection is to show the possibility to reconstruct a 3D track. This is a key point as the required exposure is decreased by an order of magnitude between 2D read-out and 3D read-out [2].

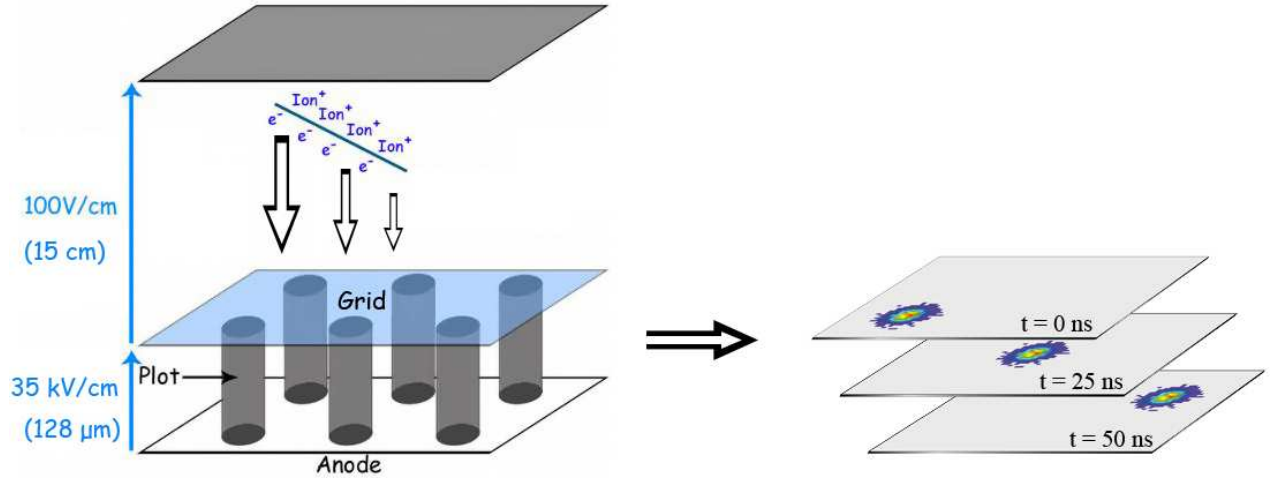The 3D reconstruction strategy chosen for the MIMAC project is the following (see fig. 4) : i)

Figure 4. Track reconstruction in MIMAC. The anode is scanned every 25 ns and the 3D track is recontructed, knowing the drift velocity, from the serie of images of the anode.

the electrons from the track are projected on the anode thus allowing to access information on x and y coordinates, ii) the anode is read every 25 ns, iii) knowing the drift velocity[2], the serie of images of the anode allows to reconstruct the 3D track.

The anode, composed of x and y stripes with 200 μm pitch, is read every 25 ns by a dedicated ASIC ship designed and built at LPSC.

Simulation of the principle of the 3D track reconstruction can be achieved with a rather good resolution, of the 0.3mm on the track length and below $4°$ on θ and ϕ [24].

Very first track reconstruction have been recently obtained with 5 MeV α from Radon impurities. Figure 5 presents an α 3D track obtained at 800 mbar in a Helium + 5 % isobutan mixture. This can be taken as a proof of the principle of track reconstruction strategy chosen for this project. Same results should be achieved in the near future with low energy recoils (below 6 keV), in the range of interest for Dark Matter.

5. Conclusion

In summary, this first measurement of Helium ionization in Helium down to energies of 1 keV recoil opens the possibility to develop a Helium μTPC for Dark Matter. 3D track reconstruction proof on principle, from simulation and α data is a first step toward a gaseous TPC aiming at directional detection of Dark Matter.

6. References

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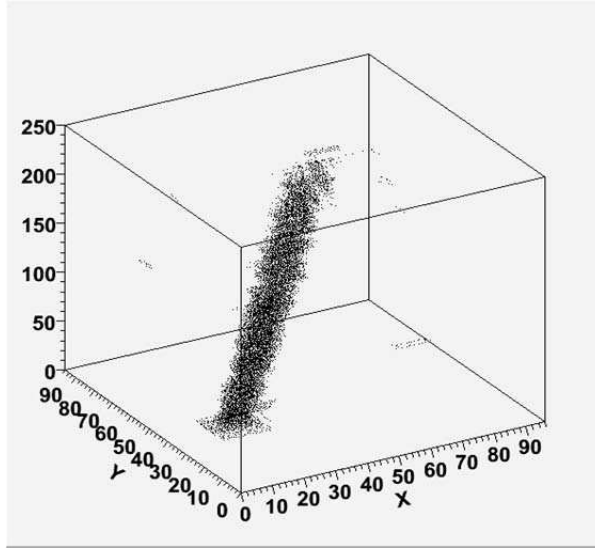[2] The value 26 μm/ns is used for simulation at 1 bar[24]

Figure 5. First result on 3D track reconstruction obtained with 5.59 MeV α from Radon impurities, at 800 mbar in a Helium + 5 % isobutan mixture.

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